

Sea Ice Mechanics Research

Max D. Coon
NorthWest Research Associates, Inc.
P.O. Box 3027
Bellevue, WA 98009-3027
phone: (425) 644-9660, x332 fax: (425) 644-8422 e-mail: max@nwra.com
Contract #: N00014-98-C-0179
<http://www.nwra.com>

LONG-TERM GOAL

The ultimate goal of this research is the development of a complete ice dynamics model that will include lead direction and ice thickness distribution in refrozen leads.

OBJECTIVES

NorthWest Research Associates, Inc. (NWRA) had two objectives during this past year. The first was to use stress data to develop a new formulation of ice strength to be used in the anisotropic model (Coon et al., 1998). The new formulation was developed and has been provided to Dr. R. S. Pritchard for his use in model development for PIPS3.0. The second objective for this year was to review other work being done on sea ice strength in Europe.

APPROACH

The approach this year was to use measured sea ice stress and models to formulate the behavior of refrozen leads. Some of the data in the models was acquired by visits to several European universities. These visits were accomplished through an appointment as Adjunct Scientist to the International ONR Office in London.

WORK COMPLETED

The work with SIMI stress data analysis was completed and the results were presented in a paper, "Determination of Pack Ice Stress from Flatjack Sensors," submitted to the *Journal of Cold Regions Science and Technology*. Douglas C. Echert, Gerald S. Knoke and myself authored this paper. Important insight into sea ice strength was gained through visits to the Technical Universities of Denmark, Finland, and Norway, as well as a visit to the Scott Polar Institute of Cambridge University in England. On each visit, I made a presentation on the development of the Anisotropic Sea Ice Model and received useful review of the model. The findings from the visits are presented in the section below. The results of this year's work were also presented at the PIPS3.0 development meeting at NIC in July.

RESULTS

During my six-month visit to the Technical University of Denmark, I worked with Leif Toudal on a frazil/pancake ice model for the Greenland Sea that may have applications in support of PIPS3.0 for

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 1999		2. REPORT TYPE		3. DATES COVERED 00-00-1999 to 00-00-1999	
4. TITLE AND SUBTITLE Sea Ice Mechanics Research				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Northwest Research Associates, Inc,P.O. Box 3027,Bellevue,WA,98009-3027				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 4	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

the marginal ice zones. Other European travel was funded through the International ONR Office in London. At the Technical University of Finland, they are working on ridge-building forces and the strength of partly consolidated ridges. The work on ridge-building forces is reported by Lensu et al. (1998) and may be particularly important for ridges in the marginal ice zone. There is also a large-scale field experiment determining the strength of first-year ridges by utilizing a large-scale, one meter, downward punch test through the ridge keel. The results may be of value in determining ridge strength for the anisotropic model (Coon et al., 1998). There is work at the University of Norway on the development of a thermodynamic model for the consolidation of first-year ridges (see Løset et al., 1998). This model development is also supported by annual field experiments. The results from this work may be important for the thermodynamic consolidation of ridges as they fit into an anisotropic model. At the Scott Polar Institute, they are involved in a European project called Local Ice Cover Deformation and Mesoscale Ice Dynamics-Ice State. The objectives of this project are:

1. To describe and model the processes involved in local ice cover deformation, such as ridging and rafting, and to incorporate these into governing equations of mesoscale ice dynamics; and
2. To identify a set of ice cover parameters that is adequate to describe an ice state, which can ideally be derived from remote sensing data and used in practical navigation.

The results from this project may aid in data assimilation for the PIPS3.0 model.

For the anisotropic model of Coon et al. (1998), it is important to develop a simple relationship between the force to build a ridge and the thickness of the thinnest ice in the lead. Considerable model calculations and data collection related to this problem have been performed. The results of these investigations can be summarized in a simple equation:

$$F = 110h^{3/2} \quad (1)$$

where F is the ridge-building force in KN/m and h is the ice thickness in meters. In an isotropic model, F would be the lead strength and h the thinnest ice in the lead. This equation is a good approximation to the average ridge building force and the viscoelastic-buckling load for a lead (for loads of six-hour duration). This is in good agreement with Parmerter and Coon (1973) (for friction of 0.3); Coon and Lau (1990); Coon et al. (1989a, 1989b); and Hopkins (1998).

The drift predicted by a sea ice model for weak ice is essentially that of free drift where ice strength is zero. That is to say, the strength term in the momentum equation is small by comparison to other terms. This will be the situation as the ice cover forms in the marginal ice zones. Therefore, it seems reasonable to ask the question, how long can the new ice in the marginal ice zone be modeled adequately with a free-drift dynamics model? One can get an estimate of this time by examining the growth of sea ice from zero to some thickness, which provides a ridging strength [given in Eq. (1)] large enough to be important in the sea ice dynamics models.

From isotropic ice dynamics model calculations, it is known that for ice strength of 10 KN/m the ice motion is free drift, 100 KN/m is strong isotropic ice and the motion departs from that of free drift considerably. In an anisotropic model there are two strengths: one for leads, which is from zero to the value given in Eq. (1) and a second strength for the ice that contains the leads, which is 250 KN/m (Coon et al., 1998). It would appear that for the marginal ice zone that a ridge strength between $\frac{1}{2}$ and

1 times the isotropic strength could be modeled as free drift. The ice thicknesses associated with these strengths are:

Free drift: $F = 10$ KN/m and Eq. (1) gives $h = .2$ m

$\frac{1}{2}$ of isotropic strength: $F = 50$ KN/m and Eq. (1) gives $h = .59$ m

Full isotropic strength: $F = 100$ KN/m and Eq. (1) gives $h = .94$ m

Attention can now be turned to the time period required to grow ice to thickness of .2 m, .59 m, and .94 m in the marginal ice zone. The first ice to form is frazil and pancake ice. Its thickness is determined primarily by wind speed [see Martin and Kauffman (1981), Bauer and Martin (1983), and Alam and Curry (1998)]. In the work on frazil and pancake ice done by Toudal and Coon (1999), a simple approximation to the ice thickness can be given by

$$h = -12 + 2.7 Va \quad (2)$$

where Va is the 10 m wind speed in m/sec for $Va > 4.3$.

After an ice cover has formed, the ice growth is governed by cumulative freezing days in $^{\circ}\text{C}$ as given by Zubov (1944) to be:

$$h^2 + 50h - 8R = 0 \quad (3)$$

where R is cumulative freezing days in $^{\circ}\text{C}$.

As an example, it will be assumed that when the ice cover forms, there is $Va = 12$ and thereafter, the temperature is -20°C . Then the frazil and pancake ice would first form to a thickness of 0.2 m as given by Eq. (2). The question now becomes, how long will it take to grow the ice to .59 m and .94 m. From Eq. (3)(with a temperature of -20°C) it will take:

9 days to grow .2 m of ice;
40 days to grow .59 m of ice; and
84 days to grow .94 m of ice.

It can now be seen that in this example, the .59 m of ice can be grown in $40 - 9 = 31$ days and the .94 m of ice can be grown in $84 - 9 = 75$ days. The first .2 m is grown by the action of the wind [Eq. (2)] so the nine days required to grow it by freezing can be subtracted from the total number of days that would be required to form it from freezing.

The conclusion from this is: The ice in the marginal ice zone can be modeled as free drift for the first one to two months.

REFERENCES

- A. Alam and J.A. Curry. 1998. Evolution of New Ice and Turbulent Fluxes over Freezing Winter Leads, J. Geophys. Res., 103, 15,783-15,801.

- J. Bauer and S. Martin. 1983. A Model of Grease Ice Growth in Small Leads, *J. Geophys. Res.*, 88, 2917-2925.
- M.D. Coon and P.A. Lau. 1990. The Effect of Viscoelastic Sea Ice Behavior on Limited Driving Forces. *Proceedings of the 1990 Offshore Technology Conference*, 4, Richardson, TX, pp. 193-200.
- M.D. Coon, G.S. Knoke, and P.A. Lau. 1989a. Time Dependent Effects on Ridge Initiation in Sea Ice Leads, *OCEANS '89 Proceedings*, IEEE Publication, 1298-1303.
- M.D. Coon, G.S. Knoke, D.C. Echert, and R.S. Pritchard. 1998. The Architecture of an Anisotropic Elastic-Plastic Sea Ice Mechanics Constitutive Law, *Journal Geophysical Research*, 103(C10), 21,915 – 21,925.
- M.D. Coon, P.A. Lau, S.H. Bailey, and B.J. Taylor. 1989b. Observations of Ice Floe Stress in the Eastern Arctic, *Proceedings, POAC '89, The 10th International Conference on Port and Ocean Engineering under Arctic Conditions*, 1, Luleå, Sweden.
- M.A. Hopkins. Four Stages of Pressure Ridging. 1998. *Journal of Geophysical Research*, 103(C10), 21,883 – 21,891.
- M. Lensu, J. Tuhkuri, and M. Hopkins. 1998. Measurements of Curvilinear Ridges in the Bay of Bothnia during the ZIP-97 Experiment. Report M-231, Helsinki University of Technology.
- S. Løset, a. Langeland, B. Bergheim, and K.V. Høyland. 1998. Geometry and Physical Properties of a Stamucha Found on Spitsbergen, *Proceedings of 14th International Symposium on Ice*, 27-31 July 1998, Potsdam/New York, edited by Hung Tao Shen, 1, 339.
- S. Martin and P. Kauffman. 1981. A Field and Laboratory Study of Wave Damping by Grease Ice, *J. Glaciology*, 27(96), 283-314.
- R.R. Parmerter and M.D. Coon. 1973. On the Mechanics of Pressure Ridge Formation in Sea Ice. *Proceedings of the 1973 Offshore Technology Conference*.
- L. Toudal and M.D. Coon. 1999. A Frazil/Pancake Ice Model for the Greenland Sea. In preparation.
- N.N. Zubov. 1944. *The Arctic Ice, Main Northern Sea Route*, Publishing House, 360 pp.

PUBLICATIONS

- Coon, M.D., Echert, D.C., and Knoke, G.S. 1998: Determination of Pack Ice Stress from Flatjack Stress Sensors, *Cold Regions Journal*, submitted.